# Gravitational Radiation Rocket

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Gravitational waves from the coalescence of binary black holes carry away linear momentum, causing center of mass (COM) recoil. This "radiation rocket" effect has important implications for systems with escape speeds of order the recoil velocity. We revisit this problem using black hole perturbation theory, treating the binary as a test mass spiraling into a spinning hole. For extreme mass ratios, we compute the recoil for the slow inspiral epoch of binary coalescence very accurately; these results can be extrapolated to the equal-mass ratio regime with modest accuracy. Although the recoil from the final plunge contributes significantly to the final recoil, we are only able to make crude estimates of its magnitude. We find that the recoil can easily reach ~100–200 km/s but most likely does not exceed ~500 km/s [1]. Though much lower than previous estimates, this recoil is large enough to have important astrophysical consequences. These include the ejection of black holes from globular clusters, dwarf galaxies, and high-redshift dark matter halos.

Along with energy and angular momentum, gravitational waves (GWs) carry *linear* momentum away from a radiating source. Global conservation of momentum requires that the COM of the system recoil. This recoil is independent of the system's total mass. An intuitive description of the recoil is as follows: when two nonspinning bodies are in circular orbit, the lighter mass moves faster and is more effective at "forward beaming" its radiation. Net momentum is ejected in the direction of the lighter mass's velocity, with opposing COM recoil. When $m_1 = m_2$ the beaming is symmetric and the recoil vanishes. The instantaneous recoil continually changes direction over a circular orbit, so the COM traces a circle. Neglecting radiation reaction, this circle closes, and the recoil averages to zero over each orbit. With radiative losses, the orbit does not close, and the recoil accumulates. This accumulation proceeds until the holes plunge and merge, shutting off the radiated momentum flux and yielding a net, nonzero kick velocity.

We performed a detailed analysis of this recoil, both in the slow inspiral regime (where we calculate fairly accurate values), and in the plunge regime (where we are relegated to fairly crude approximations). The punchline of our analysis is simple: quasi-Newtonian estimates have significantly overestimated the kick velocity from anisotropic GW emission during binary coalescence. The recoil is strongest when the smaller member is deep in the strong-field of the large black hole. General relativistic effects, such as

Figure 1—
The likely range of the recoil velocity from black hole binary merger, bounded by the blue and red curves. The recoil is a function of the effective spin of the black hole system. Negative spins are retrograde inspirals, positive are prograde.
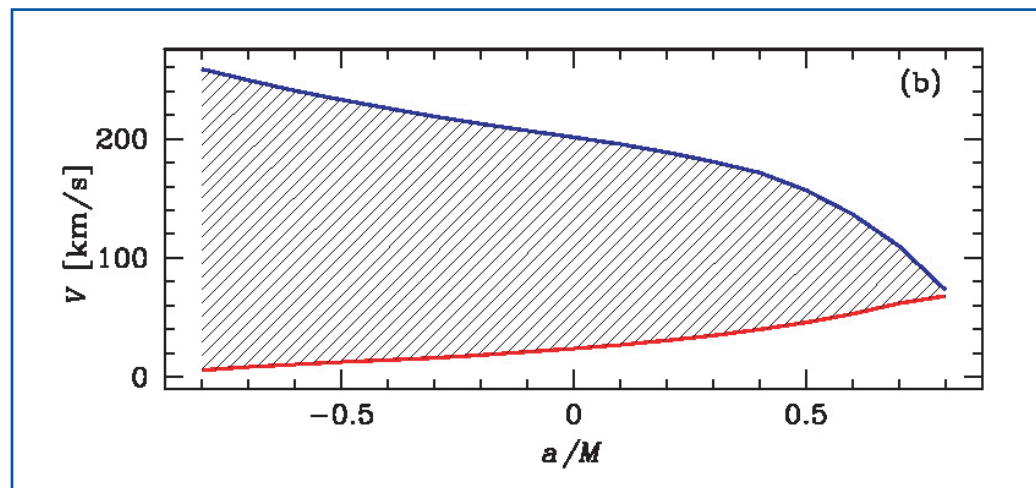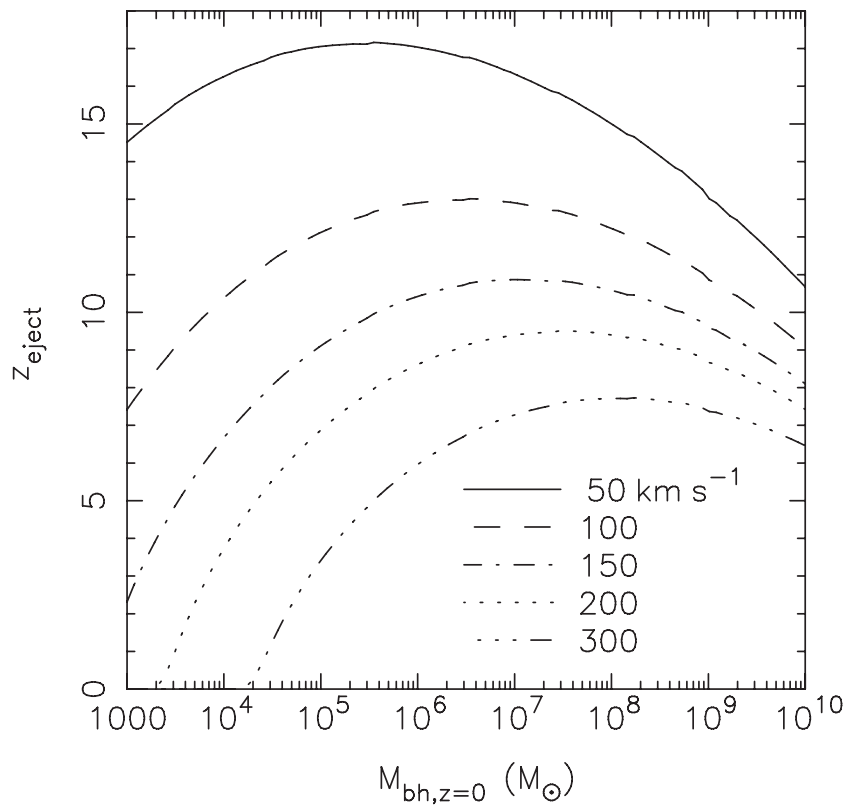
the gravitational redshift and space-time curvature-scattering, act on the emitted GWs and reduce the recoil.

Though reduced, the recoil remains large enough to have important astrophysical consequences [2]. Recoils with velocities 10–100 km/s are likely; kicks of a few hundred km/s are not unexpected; and the largest possible recoils are probably ~500 km/s. These speeds are smaller than most galactic escape velocities, suggesting that black hole mergers that follow galaxy mergers will remain within their host structures. However, these recoils are similar to the escape speeds of dwarf galaxies, and they may be sufficient to escape from mergers in high redshift structures ($z > 5$–10). This may explain the apparent absence of massive black holes in these systems. Binary black hole ejection from globular clusters is quite likely, with significant implications for the formation of intermediate mass black holes (IMBH) via hierarchical mergers. Our recoil estimates will also be useful in simulations of supermassive and IMBH evolution in dark halos. Ejection from giant elliptical galaxies would be rare, but coalescing black holes are displaced from the center and fall back on a time scale of order the crossing time. Displacement of the black holes transfers energy to the stars in the nucleus and can convert a steep density cusp into a core. Radiation recoil calls into question models that grow supermassive black holes from hierarchical mergers of stellar-mass precursors.

[1] M. Favata, S.A. Hughes, and D.E. Holz, *Astrophys. J. Lett.* **607**, L5 (2004).
[2] D. Merritt, M. Milosavljevic, M. Favata, S.A. Hughes, and D.E. Holz, *Astrophys. J. Lett.* **607**, L9 (2004).

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